Development of High Precision and Eco-friendly MRPC TOF Detector for EIC

Alexandre Camsonne[1], Sanghwa Park[1], Yi Wang[2], Zhenyu Ye[*3], and Zhihong Ye[†2]

[1]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

[2]Department of Physics, Tsinghua University, Beijing 100084, China

[3]Department of Physics, University of Illinois at Chicago, Chicago 60607, USA

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Abstract

New generation of Multigap Resistive Plate Chamber (MRPC) can reach an intrinsic timing resolution of around 20 ps on par and could be a cost effective solution for the second EIC detector in places where large area and moderate position resolution is needed. We propose an R&D program to develop an eco-friendly MRPC detector system. We will use the simulation to optimize the MRPC design and to identify eco-friendly gas substitutes for the standard greenhouse gas mixture. We will also set up test stands to evaluate the performance of MRPCs with eco-friendly gases using integrated high-performance readout electronics.

[*]Contact PI: yezhenyu@uic.edu

[†]Co-PI: yez@tsinghua.edu.cn

1 Introduction

Precision timing detectors have wide applications in high-energy physics experiments. They have been used to identify particles using time-of-flight (TOF) information, and to improve tracking and/or calorimeter performance by incorporating the timing information of charged particle tracks. A TOF detector with a 20 ps time resolution can separate π/K up to 6 GeV/c after a 4 m flight path. Such detectors have been included in the reference detector design in the Electron-Ion Collider (EIC) Yellow Paper [1].

The EIC project detector collaboration, ePIC, has selected AC-LGAD for TOF PID and tracking in the central barrel region and forward end-cap. A main advantage of AC-LGAD is that it can provide both precise timing down to a few tens of picoseconds and spatial resolutions down to a few tens of microns. However, the cost of developing and building large area AC-LGAD detectors is quite expensive. Therefore, alternative solutions with cheaper development and construction cost are worth considering, especially in places where precise spatial resolution is not required. Such a detector based on a different technology would be particularly important for the second EIC detector at IP8 where alternative detector layout and technology choices should be considered for complementarity to ePIC.

Among various technologies, the Multigap Resistive Plate Chamber (MRPC) has been proven to be a reliable and cost-effective solution to precision timing measurement, and widely used at RHIC and LHC experiments [2–4]. The timing resolution of these existing detector systems is on the order of 100 ps, with contributions from the intrinsic resolution of the MRPC itself, the readout electronics, as well as the start time (T_0). There is also a potential issue with running these MRPC detectors due to the usage of greenhouse gases, which might be forbidden to use in EIC. Several eco-friendly gas replacements have been studied with low rate tests but only 60 ps or worse time resolution have been achieved with ultra high voltages [5].

Prototypes of new generation MRPC have demonstrated that 20 ps or better intrinsic resolution can be achieved in cosmic-ray tests using standard gas. In this proposal, we describe our plan to develop a MRPC detector system which could achieve a 20 ps timing resolution when operating with eco-friendly gases and read out by integrated high-performance front-end electronics, and thus serve as a good candidate for TOF detectors at the second EIC detector at IP8.

1.1 Previous MRPC R&D

MRPC were invented in 1990s [6, 7] and then have successfully used in multiple particle physics experiments, such as in ALICE [8] and RHIC-STAR [9]. These first-generation MRPCs already have very good efficiencies and their time resolution are typically in the range of 50 to 100 ps. Future experiments, such as ALICE and CMS at CERN, CEE at IMP [10], CBM at FAIR [11] and SoLID at Jefferson Lab (JLab) [12], put a strict requirement of operating the MRPC under a very high rate background (up to 25kHz/cm^2), and in the meantime, still maintain very high detection efficiencies and precise time resolution.

The high rate requirement can be archived by employing $400\mu m$ thick low-resistive silicate glasses with a bulk resistivity of 10^{10} Ω, so-called black glasses, as demonstrated by the second generation MRPC developed by Tsinghua University [12–14] (Tsinghua). Even under an extremely high rate (70 kHz/cm^2), the beam test shows that Tsinghua's MRPC still has very high detection efficiency (90%) with a time resolution better than 80 ps. We note that the EIC detector is generally not in a high-rate environment so MRPC with regular glasses are sufficient (10 times cheaper). However, at a very forward region for measurements of extreme physics processes (e.g. detecting jet or fragments in eA collisions), a high-rate and precise-timing detector may be needed to reduce the pile-up effect and maintain high detection efficiency.

In the last ten years, several R&D work have shown that a 20 ps level intrinsic time resolution on MRPC detectors can be achieved by reducing the thickness of each gas layer down to 100 μm and stacking more layers. The most recent MRPC designed for the ALICE-TOF upgrade showed an intrinsic time resolution of 25 ps [15,16] at a low rate using regular glasses and the time resolutions become 36 ps and 50 ps at 2 kHz/cm^2 and 100 kHz/cm^2 when using the black glasses [17]. In a previous EIC R&D project (EIC RD2013-5 [18]) a thin-gas-gap MRPC prototype developed by members of the collaboration (UIUC and BNL) provided an 18 ps time resolution with the cosmic ray (25 ps in-beam at 80Hz/cm^2). However, these results were obtained with greenhouse gasses, which might be forbidden to use at EIC. Their performance in a realistic experimental environment has not been demonstrated yet.

1.2 Sealed MRPC

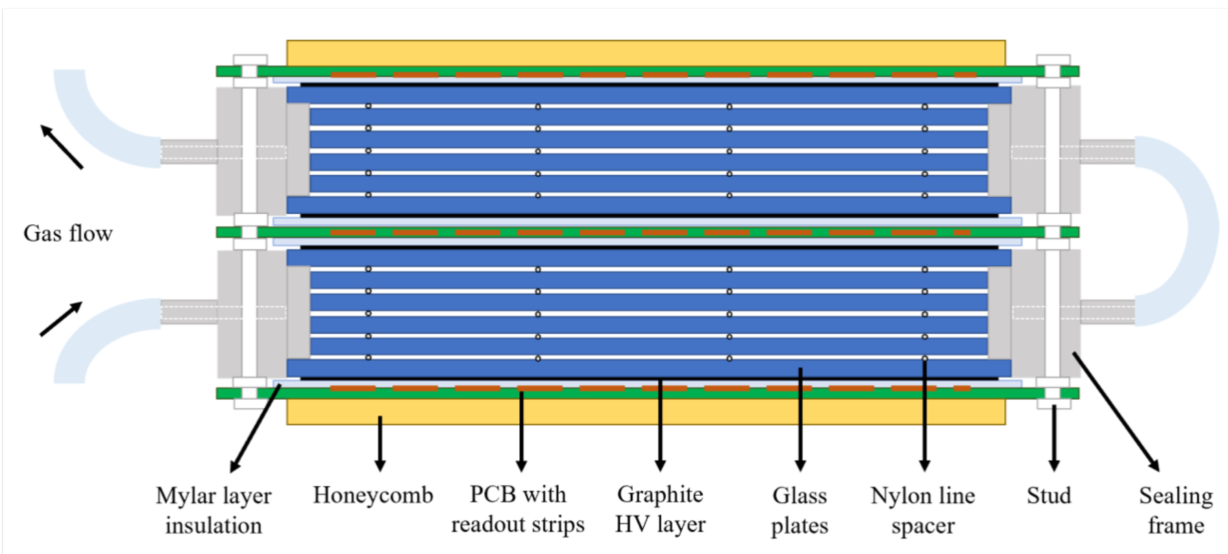
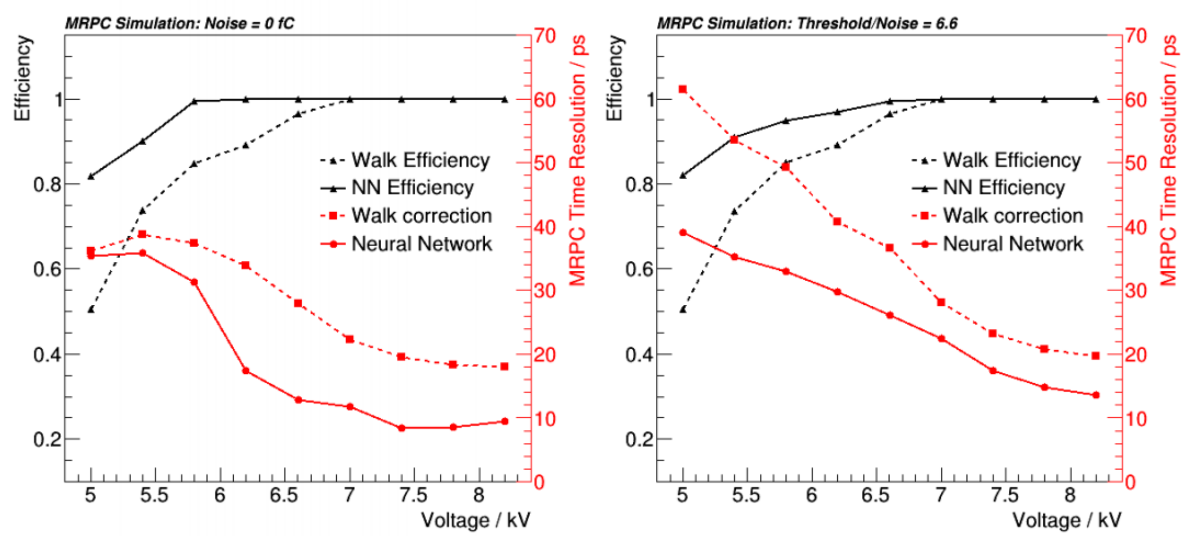


Figure 1: Scheme layout of the sealed MRPC (sMRPC) developed at Tsinghua University [19]

Tsinghua University has a long history of developing and constructing MRPC for RHIC-STAR [20,21], CBM, CEE, NICA [22], SoLID and EicC [23]. In the recent year, a brand new generation (gen-3) of MRPC has been developed (Fig 1) and it contains 32-gap with a gap thickness of 104μm [19,24]. Black glasses are used when a high-rate measurement is required, otherwise regular glasses are used. Instead of putting the entire detector in a gas box, the new MRPC also has a self-sealed structure [25] which can dramatically reduce the amount of greenhouse gas released to the atmosphere (20 cc/minute/cm^2). Such an achievement is extremely important for environmental protection point of view before eco-friendly gas replacements are identified.

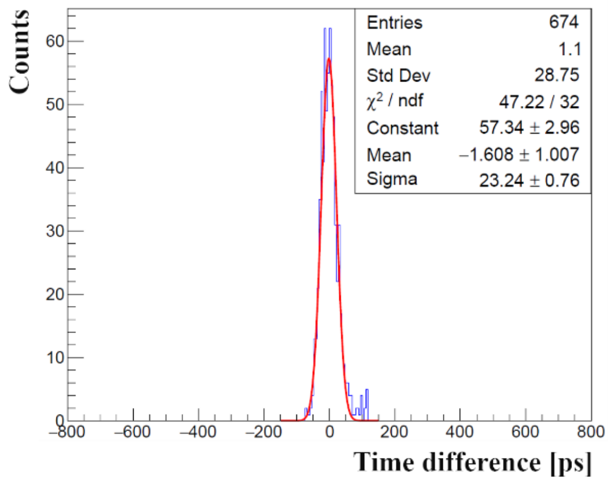
Based on simulation, the intrinsic resolution of this sealed MRPC (sMRPC) can be as low as 10 ps [26] (Fig. 2). The conventional Time-Over-Threshold (ToT) method by setting a fixed threshold during the measurement can not accommodate such a high resolution MRPC as it is largely limited by the resolution of the TDC electronics, the variation of the incoming signals (time-slewing), as well as the signal-to-noise ratio (SNR). For more precise resolution, it is essentially important to fully map out the raising edge of the timing signal. The front-end electronics is thus planned to be a fast amplifier and a charge digitizer, in order to record the waveform of signals from the detector. For example, a CAEN waveform digitizer DT5742 (based on DRS4-V5 Chip) can collect up to 8 samples of the raising edge from a sMRPC signal.

The timing performance was studied in a cosmic ray test using two identical sMRPC with gas mixture of 90% Freon (R-134a), 5% iso-butane and 5% SF6, so called the standard gas. The waveform of the sMRPC signals were measured with an amplifier with the bandwidth of 350MHz and the DT5742. A 10GS/s sampling rate Lecroy oscilloscope was also used in measuring the waveform as reference. A time resolution of 19 ps was achieve for a sMRPC in the test after the time slewing correction, as shown in Fig. 3.(a). The time resolution under high rates was also studied by exposing the sMRPC with X-rays at 55kV and 0.55μA which gives a background rate of 15kHz/cm^2 during the cosmic ray test. The study shows that the time resolution reduces to about 20ps (Fig. 3.(b)). A time reconstruction method based on the neural network (NN) and machine learning algorithms developed by Tsinghua (called ComLSTM, see [26]) took the full sampling waveform to obtain time-resolution of 10ps with no noise or 16 ps with noise without additional corrections [26, 27].

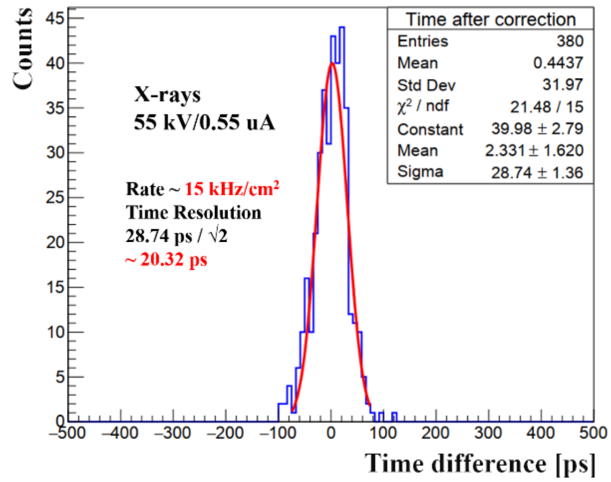


(a) (b)

Figure 2: The MRPC simulation results [26] using sMRPC (gen-3, 32-gaps, 104μm gap size). The plots show the timing resolution and efficiencies as functions of high-voltages obtained with the ToT method and the NN method. (a) are results with no noise added in the simulation and (b) has electronics noise added with a threshold/noise ratio equal to 6.6.



(a) Low rate



(b) High rate

Figure 3: The time difference between two identical MRPC after time-slewing correction [19]. Each MRPC has a resolution of $23.24/\sqrt{2} = 16.42$ ps at low rate and $28.74/\sqrt{2} = 20.32$ at high rate (15kHz/cm^2).

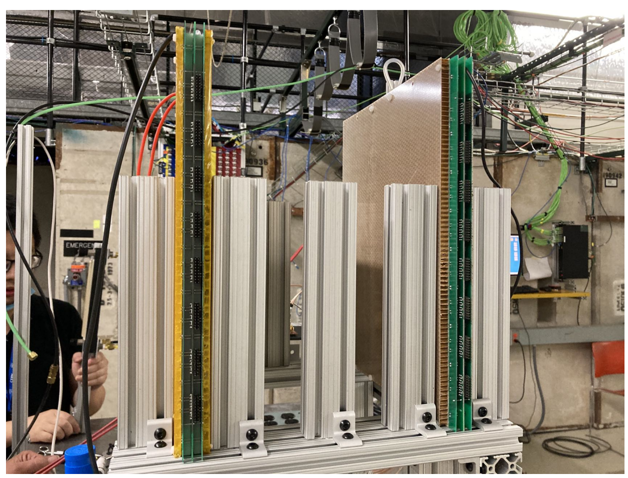


Figure 4: Two sealed MRPC were installed at Fermi-Lab Test Beam Facility.

Four new sMRPC modules produced by the Tsinghua group had been shipped to University of Illinois at Chicago (UIC). We installed two modules in the FermiLab Test Beam Facility (FTBF) in the Summer of 2022 as shown in Fig. 4 and tried to study their in-beam performance. However, due to lack of high-performance readout electronics, we were not able to obtain useful data within the approved beam-time. Two of detectors are now in the process of transferring to JLab in the Summer of 2023 while other two remain at UIC for the development of readout electronics. In this proposal, we plan to study the performance of these sMRPC using different eco-friendly gas-mixtures with cosmic rays, and possibly perform the beam test in one of the experimental halls at JLab. See the next section for our detailed R&D plan.

With the mature technology and cost effectiveness, the sMRPC can be considered by the EIC TOF community in Detector-2, such as in the forward hadron endcap region right before the calorimeters where a cost-effective TOF detector with a larger area at larger distance than Detector-1 could be more beneficial for the physics program. With the support from the EIC generic R&D plan, we plan to study and improve the performance of the sMRPC with eco-friendly gas using the cosmic-ray test. Such a TOF detector with a time resolution of 20 ps or better will enable a clear π/K separation above 6 GeV/c and serve as as a good candidate for large area TOF detectors at the EIC Detector-2.

2 Proposed R&D program

In this proposal, we focus on understanding and evaluating the performance of the sMRPC with eco-friendly gasses using integrated high-perofmrnace front-end electronics.

The standard gas mixture for MRPC is 90% Freon, 5% iC_4H_{10}, 5%SF6. Tsinghua's sMRPC typically uses 20cc/minute of gas for a 1m^2 area MRPC and the gas are released into the atmosphere if not recycled. For the EIC Detector-1, the total TOF area is about 20m^2. Assuming a whole year of running, 210 m^3 of the gas will be released into the air. Even thought the standard gas is cost-effective and proven to achieve high timing performance, it is not environmentally friendly and soon to be forbidden to be used in all U.S. national labs. It becomes very important to identify the most effective eco-friendly gas replacements for the MRPC that can still provide high timing-performance.

Many experimental studies [5, 28–32] have been performed to identify eco-friendly gases that can potentially replace the greenhouse gas. So far, a good replacement gas is a mixture of $C_3H_2F_4$ (R1234ze) and CO_2 (or SF6). Other possible candidates are Argonne+CO_2 mixtures. However, the studies are never concluded as these replacements always have pros and cons, for example, some gasses are extremely expensive (e.g. R1234ze), some have an impact on the detector systems (e.g., Helium) and most of them require ultra HV to reach good efficiencies and resolutions. The long-term stability effect among different gas replacements was also not studied in detail. The performance is also related to the designed structure of the MRPC and how the test was performed (e.g, cosmic-ray tests vs beam tests). Overall, most of previous studies focused on the detection efficiencies while the best time resolution with eco-friendly gases is 60 ps or worse [5].

2.1 Simulations

An initial simulation study was done at Tsinghua [33] to simulate the working gas performance in MRPC. Fig. 5 shows the simulation results of the MRPC with two different gas mixtures. The detection efficiencies and time resolutions in the simulation agree very nicely with the experimental data from cosmic ray tests. It suggests that the simulation toolkit can reasonably model the MRPC and its performance.

We plan to develop more advanced simulation software to explore other gas mixtures and identify a list of possible candidates that could be cost-effective while providing good performance. The simulation will be first verified for the gas mixtures fully studied by other

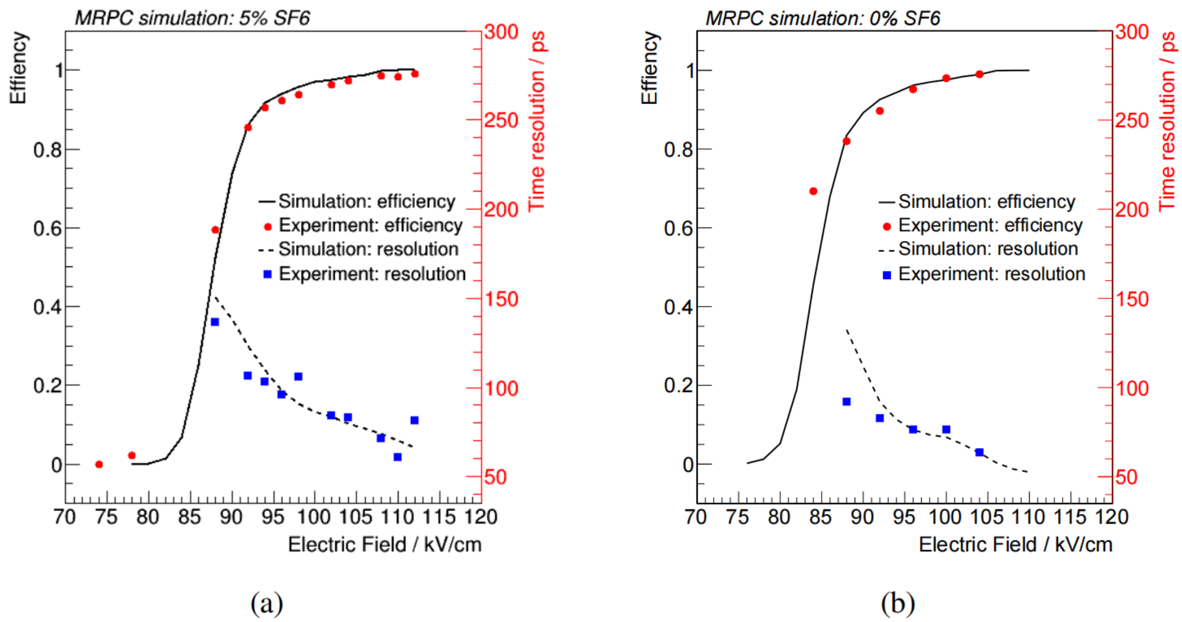


Figure 5: The MRPC simulation results were compared with experimental data for two different gas mixtures.

groups and cross-checked with the existing test results. We will make following improvements to the simulation to better describe gas properties and to better understand the performance of the sMRPC.

- Implement an advanced version of the Magboltz program, so-called the Betaboltz program [34] which is believed to describe the gas properties better and is also constantly maintained and extended by a broader community.
- Implement the space charge effect into the simulation based on the work [35] which was not considered in the simulation. It can better simulate the detector inefficiencies.
- Implement a 3D electrostatic weighting field instead of using a 1D field, based on a previous study done by Tsinghua [36]. It can simulate the charge distribution in the anode plane.
- Implement the charge sharing effect among neighboring strip. The original simulation assumed the strip closet to the gravity center of the shower picks up all the charges. The improved algorithm can determine how each strip picks up a certain portion of the avalanche signal and generates different pulses on both ends depending on the hit location and shower developments.

2.2 Characterization at UIC

Two MRPC detectors will be stationed at UIC for the cosmic ray test. A new gas mixing system will be designed and fabricated at UIC to be able to test different eco-friendly gas mixtures to evaluate the detector performance and compare to simulation results.

The performance of the sMRPC will be evaluated with cosmic rays using the most-advanced highly-integrated front-end electronics system. We propose to perform the test with cosmic-ray using the 32-channel waveform digitizer based on SAMPIC [37] chips which provides better than 5 ps time resolution, and up to 10GS/s sampling rate with 1.6GHz bandwidth. In principle, the SAMPIC meets the requirement of obtaining the intrinsic timing resolution of the sMRPC yet its realistic performance should be evaluated. Another alternative and possibly more cost-effective solution is to use the 128-channel pico-TDC chips [38] which provides also close to 5 ps resolution for each TDC channel and can potentially still achieve good timing resolution using the ToT method when the background noise is small and the experimental rate is low like the EIC environment. The performance of the SAMPIC will be tested and compared with pico-TDC.

2.3 Beam test at JLab

With the eco-friendly gases identified from the simulation and cosmic test, we propose to setup two MRPC detector planes in the JLab experimental hall (e.g, Hall-C) and study its performance under high-energy radiation background with various rates. The experimental halls at JLab can offer large background parasitically to running experiment.

3 Budget request

Tsinghua: One full-time student will work on the simulation of sMRPC with eco-friendly gas and closely work with UIC and JLab to analyze the cosmic data (0.5 FTE, fully supported by Tsinghua, no funding requested). Tsinghua will provide the picoTDC boards. The student will travel to US to work on the cosmic test setup and analysis ($10K) and to JLab for beam test ($10K). In a scenario of reduced budget, the student will find other support for traveling to US or just skip the trip.

UIC: UIC needs to purchase the gas mixing system and different gas mixtures ($40K total). In addition, UIC will buy a HV supply ($10K) and two SAMPIC modules ($5K×2), as well as the cost for traveling to JLab for beam tests is about $10K. One FTE graduate student with 0.5 FTE ($25K) supported by the project and the rest covered by other resources will work on the simulaiton, cosmic-ray and beam tests, perform data analysis and compare results with simulation data.

JLab: JLab will purchase the MRPC gas mixtures and other small accessories for the local beam test ($5K).

In total, we request a budget of $120K to support the tasks layed out in this proposal. Table 1 gives the detailed breakdown of the budget to be shared among three teams for different tasks. Tsinghua takes the lead of the software development and the data analysis. UIC will focus on setting up the cosmic test. Tsinghua and UIC will work together on studying the eco-friend gasses by performing both the simulation study and the experimental tests. For the "Cosmic/Beam Test", Tsinghua's cost is mostly the travel cost, UIC's cost is mainly for purchacing equipment, the gases, and travel.

	Personnel	Gas System	Cosmic Test	Beam Test	Sum
Tsinghua	-	-	$10K	$10K	$20K
UIC	$25K	$40K	$20K	$10K	$95K
JLab	-	-	-	$5K	$5K
Total	$25K	$40K	$30K	$25K	$120K

Table 1: Money Matrix

In a scenario of 80% of the requested budget is granted, UIC will purchase one SAMPIC module only ($5K less) and Tsinghua and UIC will skip the trip to JLab ($20K less).

In case of only 60% of the requested budget is given, UIC will reduce the funding for supporting the student from 0.5 FTE to 0.3 FTE. We will skip the beam test hence reduce the $5K for gas purchase at JLab, and reduce travel cost to zero. Tsinghua will skip the travel to UIC or look for alternative sources to support the travel.

Detailed tables in the following sections reflect different budget scenarios.

3.1 Detailed budget full funding

Tsinghua University	Travel	$20K
UIC	0.5 FTE student	$25K
UIC	Gas system	$30K
UIC	Gas supplies	$10K
UIC	HV supply	$10K
UIC	SAMPIC×2	$10K
UIC	Travel	$10K
JLAB	Gas supplies	$5K
Total		$120K

3.2 80 % budget scenario

Tsinghua University	Travel	$10K
UIC	0.5 FTE student	$25K
UIC	Gas system and gas	$40K
UIC	HV supply	$10K
UIC	SAMPIC	$5K
JLAB	Gas supplies	$5K
Total		$95K

3.3 60% budget scenario

UIC	0.3 FTE student	$15K
UIC	Gas system and gas	$40K
UIC	HV supply	$10K
UIC	SAMPIC×1	$5K
Total		$70K

4 Diversity, Equity, and Inclusion

The members of this proposal are attuned to the importance of diversity, equity and inclusion (DEI) in physics and are fully committed to promote the DEI though the proposed research program. Zhihong Ye and Zhenyu Ye have mentored several students from underrepresented groups. Tsinghua university has a diverse community with international students from more than 100 countries. UIC has a strong commitment to enhancing DEI via various university programs such as Advancing Racial Equity initiative and community engagement. As a university faculty, Zhihong Ye and Zhenyu Ye will involve students in this proposed research and create an inclusive and supportive environment.

Sanghwa Park has been serving at the EIC User Group (EICUG) DEI committee since 2020. As a member of the committee, she worked on developing the value statement and code of conduct for the EICUG, and conducted a DEI survey in 2021 and 2022. She mentored an undergraduate student (eRD26) and a postdoc (eRD110) from Mississippi State University throughout the other EIC R&D programs. Alexandre Camsonne has mentored several students and postdocs from underrepresented groups at Jefferson Lab. Jefferson Lab has been supporting students (from high school to graduate) as well as postdocs throughout various programs such as SULI, REU and CCI. The lab's Diversity, Equity, Inclusion and Accountability program aims to foster an inclusive environment for researcher from all over the world. Camsonne and Park are staff scientists at Jefferson Lab and will involve students from underrepresented groups into the proposed R&D program.

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